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Neutron Stars in Supernova Remnants and Beyond

Vasilii V. Gvaramadze
Sternberg Astronomical Institute, Moscow State University, Universitetskij Pr. 13, Moscow, 119992, Russia

Abstract. We discuss a concept of off-centred cavity supernova explosion as applied to neutron star/supernova remnant associations and show how this concept could be used to preclude the anti-humane decapitating the Duck (G 5.4−1.2 + G 5.27−0.9) and dismembering the Swan (Cygnus Loop), as well as to search for a stellar remnant associated with the supernova remnant RCW 86.

1. Introduction

Massive ($\geq 8 - 10\,M_{\odot}$) stars are the progenitors of most of supernovae (SNe). The explosion of a massive star results in the origin of an extended (tens of parsecs) diffuse supernova remnant (SNR) and a compact stellar remnant. In most cases the stellar remnant is a neutron star (NS). Therefore most of SNRs should be associated with NSs. A NS could be located within the confine of the associated SNR or beyond it, depending on the kick velocity received by the star, the age of the system and some other factors (see below). However, only a small fraction of known SNRs was found to be associated with NSs. Moreover, it is believed that some of proposed NS/SNR associations are the result of geometrical projection. Thus, the obvious lack of associations should be explained or filled up. The latter seems to be more attractive and fruitful in view of the recent splash of discoveries of NSs in SNRs.

The reliability of NS/SNR associations is usually assessed with help of several criteria (see e.g. Kaspi 1996). Some of them are trivial, i.e. should be fulfilled for any association. Other criteria are based on the use of the standard Sedov-Taylor model of SNRs and therefore are over-simplified. The application of these criteria can lead to rejection of genuine associations (Gvaramadze 2000, 2002a,b; Bock & Gvaramadze 2002). The point is that the massive stars strongly modify their environs by virtue of their winds and ionizing emission, and it is the subsequent interaction of SN blast waves with their processed ambient medium that results in the observed SNRs (e.g. Shull et al. 1985; Ciotti & D'Ercole 1989; Chevalier & Liang 1989). It is clear that the presence of circumstellar and interstellar structures could strongly affect the standard sequence and duration of evolutionary stages of the SN blast wave (e.g. Woltjer 1972). For example, the Sedov-Taylor stage could be absent at all if the SN exploded within the wind-blown cavity surrounded by a massive shell (e.g. Franco et al. 1991). Another important point is the proper motion of massive stars, which causes them to explode far from the geometrical centres of their cavities and makes the cavities and other circumstellar and interstellar structures non-spherically-symmetrical. The natural consequence of an off-centred cavity SN explosion is that the SN blast centre does not coincide with the geometrical centre of the future SNR. Taking into account these considerations allows us to enlarge the circle of possible NS/SNR associations and to explain the morphological peculiarities of SNRs (Gvaramadze 2000, 2002a,b; Bock & Gvaramadze 2002; Gvaramadze & Vikhlinin 2003). On the other hand, the better understanding of origin of peculiar SNRs helps to infer the "true" SN explosion sites in these remnants, and therefore to search for new NSs associated with them (Gvaramadze 2002b; Gvaramadze & Vikhlinin 2002, 2003; see also Sect. 4).

To illustrate the significance of the concept of off-centred cavity SN explosion we show how this concept could be used to preclude the anti-humane decapitating the Duck (G 5.4−1.2 + G 5.27−0.9) and dismembering the Swan (Cygnus Loop, G 74.0−8.5) recently attempted, respectively, by Thorsett, Brisken, & Goss (2002) and Uyaniker et al. (2002), and to search for a NS associated with the SNR RCW 86 (MSH 14-6*3*, G 315.4−2.30).

2. The Duck (G 5.4−1.2 + G 5.27−0.9)

The association between the pulsar B 1757−24 and the SNR G 5.4−1.2 was for a long time one of a few most reliable NS/SNR associations. However, recently this association was questioned by Thorsett et al. (2002), who suggested that PSR B 1757−24 and the compact nebula G 5.27−0.9 behind it (the "head" of the "Duck") are unrelated to the SNR G 5.4−1.2 (the "body" of the "Duck"). To justify the decapitating the Duck, Thorsett et al. used a set of standard criteria for evaluating the reliability of NS/SNR associations (e.g. Kaspi 1996), which include the agreement of distance and age estimates for pulsar and SNR, the consistence of the implied pulsar transverse velocity (i.e. the velocity inferred by the displacement of the pulsar from the geometrical centre of the SNR) with the measured (e.g. proper motion) velocity, and the correct orientation of the vector of pulsar transverse motion. We agree with Thorsett et al. (2002) that the estimates of the distance to the pulsar and the SNR are not inconsistent and therefore will concentrate on the rest three criteria.

Two main arguments against the association put forward by Thorsett et al. (2002) are based on their interferometric proper motion measurements of PSR B 1757−24 [an upper limit on the westward motion of the pulsar, $v_{\rm w} \leq 145\, d_{4.5}$ km s^{-1} ($d_{4.5}$ is the distance to the SNR in units of 4.5 kpc) was found to be an order of magnitude less than the implied transverse velocity] and the "incorrect" orientation of the pulsar proper motion (a cometary-shaped nebula behind the pulsar does not point back to the geometrical centre of G 5.4−1.2). Both "inconsistencies", however, could be removed if the SNR G 5.4−1.2 is the result of off-centred cavity SN explosion. We suggest that: a) PSR B 1757−24 was born near the northwest edge of a wind-blown cavity; b) the cavity was surrounded by a massive ($\geq 50\, M_{\rm ej}$, where $M_{\rm ej} \simeq 3-4\, M_{\odot}$ is the mass of the SN ejecta) wind-driven shell (see also Gvaramadze 2000, 2002b). The first suggestion implies that: *i*) the "true" transverse velocity of the pulsar is much smaller than the implied one; *ii*) the tail behind the pulsar has a correct orientation. The second suggestion implies that: *i*) the SN blast wave was drastically decelerated by the interaction with the wind-driven shell, so that the pulsar (moving in the westward direction at the velocity $\leq v_{\rm w}$) was able to overrun the resulting SNR; *ii*) the current radius of the SNR is about the same as the radius of the wind-driven shell.

The proper motion measurements by Thorsett et al. (2002) provide an estimate of the kinematic age of the system: $t_{\rm kin} \sim l/v_{\rm w}$, where l is the distance travelled by the pulsar from its birthplace. For $l \simeq 8\,d_{4.5}$ pc (Gvaramadze, in preparation), one has $t_{\rm kin} \geq 3\tau$, where $\tau = 1.55 \times 10^4$ yr is the characteristic age of the pulsar. The "true" pulsar age, however, could be equal to $t_{\rm kin}$ if the spin-down rate of the pulsar is mainly due to the interaction between the pulsar's magnetosphere and the dense ambient medium (see Gvaramadze 2001 and references therein), or if the pulsar braking index is ≤ 1.7 (cf. Gaensler & Frail 2000).

3. The Swan (Cygnus Loop, G 74.0−8.5)

Recent polarized intensity image of the Cygnus Loop obtained by Uyaniker et al. (2002) revealed a prominent shell-like structure encompassing the "break-out" region in the south of this SNR. Uyaniker et al. advocated the widely accepted point of view on the origin of SNRs consisting of two overlapping shells and suggested that the Cygnus Loop is actually two individual SNRs interacting with each other. An alternative possibility is that the SNRs of this type are due to off-centred cavity SN explosions (Dubner et al. 1994, Gvaramadze 2002b). We suggest that the SNR Cygnus Loop is the result of SN explosion near the south edge of a cavity blown up by the SN progenitor during the main-sequence phase (cf. Gvaramadze & Vikhlinin 2003; see also Sect. 4). This implies that the conventional shell of the Cygnus Loop corresponds to the former cavity re-energized by the SN blast wave, while the south shell is created by the interaction of the SN blast wave with the unperturbed interstellar medium. Accordingly, we expect that only one stellar remnant is associated with both shells.

Uyaniker et al. (2002) discussed eight reasons for considering the Cygnus Loop as two colliding SNRs. We note however that these reasons could also be considered as indications of the off-centred cavity SN explosion. For example, we believe that the presence of a NS candidate (Miyata et al. 2001) near the centre of the south shell is a strong argument in support of our suggestion. Note also that the absence of centrally peaked X-ray emission in the south shell implies that the SN progenitor exploded after the red supergiant phase of its evolution (cf. Gvaramadze 2002b), i.e. the initial mass of the progenitor was $< 15\,M_{\odot}$.

4. RCW 86 (MSH 14-6*3*, G 315.4−2.30)

RCW 86 is a bright shell-like SNR with a peculiar protrusion in the southwest encompassing a prominent hemispherical optical nebula. We believe that RCW 86 is the result of a cavity SN explosion of a moving massive star, which after the main-sequence phase has evolved through the red supergiant phase, and then experienced a short "blue loop" (Gvaramadze & Vikhlinin 2003; cf. Gvaramadze 2002b). During the main-sequence phase the stellar wind blows up a large-scale cavity, while the motion of the star causes it to cross the cavity and start to interact directly with the interstellar medium. We suggest that the SN exploded inside a "hollow" bow shock-like circumstellar structure (created by the post-main-sequence winds) adjacent to the main-sequence cavity. This suggestion implies that the optical arc in the southwest of RCW 86 is the remainder of the pre-existing circumstellar structure and that the stellar remnant associated with the SNR should be in the centre of the arc.

Motivated by these considerations we searched for a stellar remnant in the southwest protrusion of RCW 86 using the *ROSAT* and *Chandra* archival data. The unprecedented high angular resolution of the *Chandra X-ray Observatory* allows us to detect a NS candidate just in the "proper" place (see Gvaramadze & Vikhlinin 2002, 2003).

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